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Rainfall Frequency and Global Change Model Options for the City of Alexandria, Virginia

PREPARED FOR: City of Alexandria
Transportation & Environmental Services Department

PREPARED BY: Phillip Pasteris/CH2M HILL
Lee Traynham/CH2M HILL

COPIES: Laurens van der Tak/CH2M HILL

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Introduction

The City of Alexandria, Virginia, (City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of this project is to provide a program that, over a period of up to five years, will analyze storm sewer capacity issues, identify problem areas, develop and prioritize solutions, and provide support for public outreach and education.

The purpose of the first task is to review and propose revisions to the City's stormwater design criteria, through a series of four subtasks.

The purpose of subtask 1.3 is to provide the City of Alexandria with potential of changes in precipitation intensity, duration, and frequency (IDF) values based on the results of global climate models paired with a range (low to high) in greenhouse gas emission scenarios. Subtask 1.3 builds on the analysis performed in subtask 1.2 to identify the appropriate stations and data record lengths needed to characterize IDF values in the Alexandria, Virginia, area.

The other three Task 1 subtasks that will develop recommendations for updating the City's stormwater design criteria include the following:

- Subtask 1.1 - Comparison of Alexandria's Storm Design Criteria to Neighboring Jurisdictions
- Subtask 1.2 – Updated Precipitation Frequency Results and Synthesis of New IDF Curves
- Subtask 1.4 - Sea Level Rise

Executive Summary and Recommendations

Results from 12 daily global circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in daily and annual precipitation for the years 2050 and 2100. The projected changes were applied to the historical daily precipitation record for the period 1945 to 2010 to produce updated IDF values for durations ranging from 5 minutes to 96 hours for return intervals ranging from 2 to 500 years.

The existing Alexandria, VA precipitation IDF curves can be termed conservative, meaning that for most durations less than 12 hours and return periods from 2 to 100 years, the current Alexandria IDF values are greater than the projected IDF amounts for the years 2050 and 2100. For durations greater than 12 hours, projected IDF amounts for 2050 and 2100 are greater than the existing Alexandria IDF amounts for return periods greater than 10 years.

Because of the potential infrastructure cost implications of changing drainage design criteria, the City of Alexandria is recommended to initially adopt the Atlas 14 or L-Moment results from Subtask 1.2 (which are essentially the same), which are generally lower than the City's current IDF curves, but are based on a much more complete historical data set and statistical analysis.

As part of the pilot watershed analysis of drainage facility needs in Task 2, it is recommended that the City conduct a cost-benefit analysis of the costs and risks associated with the lower Atlas 14 curves compared with the projected 2050 and 2100 IDF curves in this technical memorandum (TM) (and the sea level rise impacts on downstream hydraulic constraints). Only when costs are weighed against the risks of either reducing the IDF curves (as would be the recommendation by using Atlas 14) or increasing the IDF curves (as would be the recommendation based on projected 2100 rainfall intensities) will a better understanding of the implications of changing the City's design criteria be gained.

Rainfall Intensity, Duration, Frequency Literature Review

The primary methods used to analyze rainfall IDF are described in the National Weather Service (NWS) National Oceanic and Atmospheric Administration (NOAA) Atlas 14, Volume 2, Ohio River Basin & Surrounding States (Bonnin et al., 2004). The NOAA Atlas 14 does not provide information describing how IDF values could change based on global climate model projections. The methods are further discussed in this report.

Concerns about potential changes in precipitation IDF resulting from climate change projections were addressed by the U.S. Climate Change Science Program (CCSP) in a report titled, "Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands (CCSP, 2008). The report is subtitled "Why Weather and Climate Extremes Matter, Observed Changes in Weather and Climate Extremes, Causes of Observed Changes in Extremes and Projections of Future Changes, and Measures to Improve Our Understanding of Weather and Climate Extremes" and provides an overview of projected changes in extreme precipitation

The CCSP report states that "one of the clearest trends in the United States observational record is an increasing frequency and intensity of heavy precipitation events" (Karl and Knight, 1998; Groisman et al., 1999, 2001, 2004, 2005; Kunkel et al., 1999; Easterling et al., 2000; Intergovernmental Panel on Climate Change [IPCC], 2001; Semenov and Bengtsson, 2002; Kunkel, 2003). One measure of this is how much of the annual precipitation at a location comes from days with precipitation exceeding 50.8 millimeter (mm) (2 inches) (Karl and Knight, 1998). The area of the United States affected by a significant above normal contribution from these heavy precipitation days increased by a statistically significant amount, from about 9 percent in the 1910s to about 11 percent in the 1980s and 1990s (Karl and Knight, 1998). Total precipitation also increased during this time as a result of increases in the intensity of heavy precipitation events (Karl and Knight, 1998).

Subtask 1.3 uses projected changes in monthly and annual precipitation from climate change models to determine if precipitation trends identified in the CCSP report will affect IDF curve results.

Emissions Scenarios used as Input for Global Climate Change Models

In 2000, the IPCC published a special report on emissions scenarios (SRES) that described a family of six emission scenarios to condition global climate models, as shown on Figure 1 (IPCC, 2000). The six scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. None of the scenarios in the set includes any future policies that explicitly address climate change, although all scenarios encompass various policies of other types. The six emission scenarios were available from the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (Wigley, 2008).

To help bound the uncertainty of emission-driven projected climate change; the Alexandria IDF study used the B1 (low), A1B (medium), and A1FI (high) emissions scenarios for the target evaluation dates of 2050 and 2100. A complete description of the SRES can be found in Appendix A.

FIGURE 1
Scenarios for greenhouse gas emissions from 2000 to 2100 in the absence of additional climate policies. (IPCC, 2000)
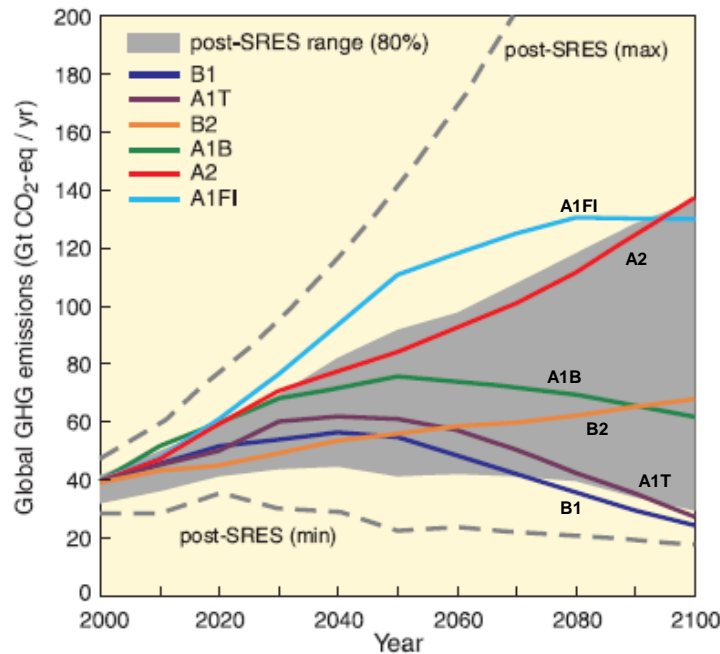
Global Climate Change Model Review and Selection Process

Computer-run, mathematical simulations or models of the atmosphere and ocean are the principal tools for predicting the response of the climate to increases in greenhouse gases. The most sophisticated of these tools are called general circulation models (GCM), which express in mathematical form, what is known of the processes that dictate the behavior of the atmosphere and the ocean. GCMs include the interaction of the atmosphere with the oceans and the surface of the Earth, including plants and other ground cover.

The ability to evaluate the strengths and weaknesses of climate models has grown over the last two decades. A growing number of GCMs, many with independently derived components, are available for intercomparison. There is a growing store of meteorological and oceanic observations against which model predictions can be tested. There is also information on past climate change, recorded by natural processes in rocks and sediments, that allow scientists to assess the ability of models to replicate the known features of climates different from that of the present day. Each of these elements is the basis for debate on the reliability of climate model projections of the future climate.

The Program for Climate Model Diagnosis and Intercomparison website contains IPCC Assessment Report 4 (AR4) model results from 12 daily general circulation models (Lawrence Livermore National Laboratory, 2010). Model results were downloaded from the site into the SimCLIM application (Warrick, 2009) for use in this project. A complete description the GCM dataset source and models are shown in Appendix B.

The combination of three emission scenarios and 12 daily GCMs provide a representative set of projections that can be used to assess the boundaries of climate change impacts on IDF curves for the Alexandria, Virginia, project area. A summary of daily GCMs, emissions scenarios, precipitation durations, return periods and selected target years for the analysis is shown in Table 1.

TABLE 1
Daily general circulation models, SRES emission scenarios, durations, return periods, and target years used to assess projected climate change impacts for stations for the Alexandria, VA region.

Daily General Circulation Models Country Origin and Grid Spacing (mi)	Emission Scenarios	Durations	Return Periods	Target Years
BCC, Norway (~105 mi)	A1FI (high)	5-, 10-, 30-minute	2, 5, 10, 25, 50, 100, 500 years	2050, 2100
CCCMA-T47, Canada (~150 mi)	A1B (medium)			
CNRM, France (~105 mi)	B1 (low)	1-, 2-, 3-, 6-, 12-hour		
CSIRO-MK3.5, Australia (~105 mi)				
GFDL 2.0, U.S. (~120 mi)				
GFDL 2.1, U.S. (~120 mi)		1, 2-day		
IPSL, France (~165 mi)				
MIROC-M, Japan (~150 mi)				
MIUB-ECHO-G, Germany/Korea (~240 mi)				
MPI-ECHAM5, Germany (~105 mi)				
MRI, Japan (~150 mi)				
NCAR-CCSM, U.S. (~75 mi)				

Sources of Observed Data, Quality Control, and Adjustments

In addition to NWS Washington Reagan National Airport, Subtask 1.3 used four additional daily climate stations in the region to provide a regional perspective of how projected climate will impact precipitation IDF as shown in Table 2.

TABLE 2
Summary of metadata for the daily precipitation stations used in the SimCLIM analysis.

NWS Station ID	Station Name	State	Longitude	Latitude	Period Selected	Years of record
18-2325	Dalecarlia Reservoir DC	MD/DC	-77.1131	38.9400	1945-2010	66
18-6350	National Arboretum DC	MD/DC	-76.9700	38.9133	1948-2010	63
18-9070	Upper Marlboro 3 NNW	MD	-76.7767	38.8653	1956-2010	55
44-8737	Vienna Tyson's Corner	VA	-77.2664	38.9000	1942-2010	69
44-8906	Washington Reagan AP	VA	-77.0342	38.8483	1945-2010	66

The daily data were analyzed to obtain annual maximum values for durations of 1, 2, and 4 days, consistent with the data used by NWS in the Atlas 14 analysis. The 1-day data were converted to 24-hour data using a conversion factor of 1.13, and the 2-day data were converted to 48-hour data using a conversion factor of 1.04, as obtained from Table 4.1.7 in Atlas 14 (Bonnin et al., 2006). No conversion factor was used for the 4-day data.

SimCLIM Application Description and GCM Processing

The SimCLIM modeling tool, developed by CLIMsystems in New Zealand, provides an environment in which the impacts of climate on the environment can be examined. SimCLIM merges historical climate information with global climate change projections to provide users with the ability to conduct sensitivity analysis and examine sector impacts of climate change. SimCLIM stores GCM results and IPCC emissions scenarios allowing a variety of options to determine the range of results from a specific GCM using a variety of available emission scenarios. SimCLIM produced daily precipitation projections from 1990 to 2100 from low,

medium, and high emissions scenarios. Daily precipitation projections are aggregated to annual totals, as shown on Figure 2.

Figure 2 indicates that 90 percent of the GCMs run with the low emissions scenario showed an increase of approximately 1.5 inches of total annual precipitation (+4%) by the year 2100. The median precipitation amounts ranged from approximately 42.8 (+7%) to 46.5 (+16%) inches by the year 2100 for low, medium and high emissions scenarios. Only 10 percent of the GCM results from the highest emissions scenario were above 50.1(+25%) inches by 2100.

FIGURE 2

Projected changes in annual precipitation for Ronald Reagan Washington National Airport using the median of 12 Daily GCMs and three SRES emission scenarios for the years 1990 to 2100. The range of ensemble results is shown for the 10, 50 and 90 percent exceedance probabilities for selected emission scenarios.
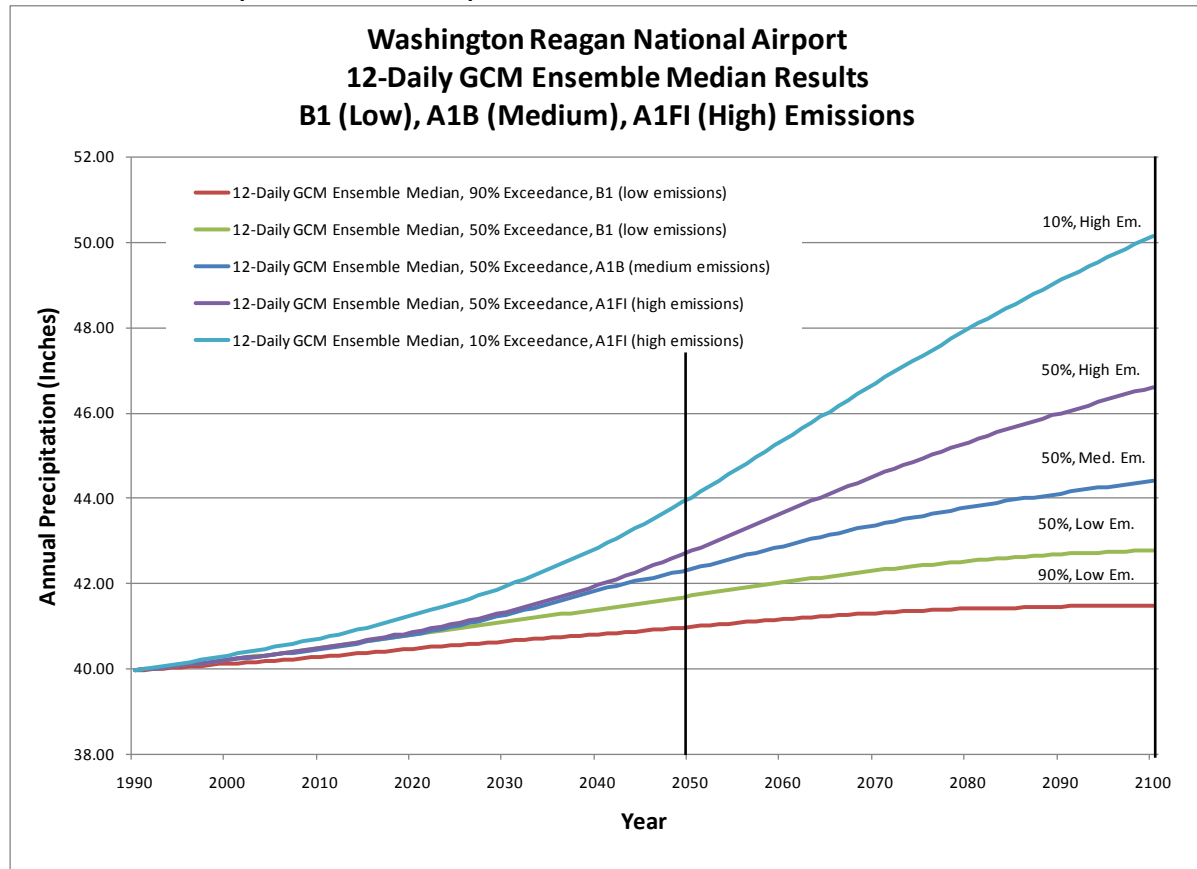
Extreme Value Analysis Approach

Past climate data can be queried through an extreme event analysis tool which can determine the probability of a particular extreme event, such as heavy rainfall. The probabilities and return periods for such extreme events are queried for the future by using the selected GCM and SRES emissions scenarios.

SimCLIM uses the generalized extreme value (GEV) analysis to model extremes of natural phenomenon as described in subtask 1.2. A complete description of the methods used can be found in Appendix C.

In summary, SimCLIM performed the following 9 steps:

1. create a GEV distribution using a GCM base period to calculate extreme precipitation intensity values,

2. create a GEV distribution for the above GCM based on its future daily data (2050 and 2100),

3. calculate the difference in percentage of the extreme precipitation intensity values of between baseline and each future period,

4.   calculate the annual global average mean temperature change between the future periods and its baseline for the above GCM,

5.   normalize the extreme precipitation changes by using linear least square regression method,

6.   using bi-linear interpolation, create a GEV distribution from data of the study region and calculate the extreme precipitation values for selected return periods,

7.   extract the change pattern values from global change patterns generated in step 6,

8.   obtain the global average mean temperature change for the selected study time slices (2050, 2100) and GHG emission scenarios (A1FI, A1B and B1) from SimCLIM, and

9.   calculate the extreme precipitation values by calculating the change patterns with global mean temperature.

Global Change Model and SRES Emission Scenario Processing

SimCLIM calculated precipitation values for durations ranging from 1 hour to 4 days and return periods from 2 to 500 years. Results from the five climate stations in Table 2 were averaged to create representative results for the Ronald Reagan Washington National Airport.

Each station's projected values for the 5-, 10-, 15-, and 30-minute durations and 1-, 2-, 3-, 6-, and 12-hour durations were scaled by the ratios derived from the NOAA Atlas 14 for each station. Applying the historical ratios to the projected 24-hour precipitation value resulted in a smooth transition for precipitation values for durations ranging from 5 minutes to 24 hours.

Ensemble climate change projections were developed for the years 2050 and 2100 from 12 daily GCMs and three SRES emissions scenarios. Projected rainfall IDF values were produced for durations of 5, 10, 15, 30, 60 minutes; 2, 3, 6, 12 and 24 hours at 2-, 10-, and 100-year return intervals.

Analysis of Results

2-year Return Period Discussion

Projected IDF precipitation intensity values for the 2-year return period derived from the SimCLIM for the period 2050 and 2100 are shown in Figure 3 and Table 3. The historical precipitation intensity values used for the City of Alexandria are higher than the values generated by SimCLIM for 2050 and 2100. The greatest differences are shown in durations, from 5 minutes to 12 hours.

Projected precipitation intensities for the year 2050 are approximately 15 to 25 percent less than the existing Alexandria intensities for durations of 5 minutes to 6 hours and approximately 8 and 11 percent less than the existing Alexandria intensities for durations of 12 to 24 hours.

Projected precipitation intensities for the year 2100 are approximately 12 to 23 percent less than the existing Alexandria intensities for durations of 5 minutes to 6 hours and approximately 5 to 8 percent less than the existing Alexandria intensities for durations of 12 to 24 hours.

It should be noted that while the existing Alexandria IDF curve is higher than the projected 2-year curve in both 2050 and 2100, the projected intensities are higher than the NOAA IDF curve used by VDOT by between 7 and 15 percent.

FIGURE 3

Projected changes in the 2-year IDF precipitation intensities for 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average compared with existing City of Alexandria, Virginia, IDF Values.

Reagan National AP, NWS ID 44-8906
Projected Mean Intensity and Duration Curves
2-Year Return Period
Derived from 5 Station Regional Average

TABLE 3

Projected changes in the Alexandria, VA 2-year IDF precipitation intensities for 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average compared with existing City of Alexandria, Virginia, IDF Values. Table includes historical NOAA Atlas 14 IDF values.

2-year Return Period	Precipitation Intensity (Inches / Hour)											
	Minutes				Hours							
	5	**10**	**15**	**30**	**1**	**2**	**3**	**6**	**12**	**24**	**48**	**96**
Historic Rainfall Intensity (Inches/Hour)												
Alexandria IDF	*6.2*	*4.8*	*4.2*	*2.8*	*1.80*	*1.15*	*0.76*	*0.45*	*0.25*	*0.14*		
NOAA (1945-2000)	*4.72*	*3.77*	*3.16*	*2.18*	*1.37*	*0.79*	*0.56*	*0.34*	*0.20*	*0.12*	*0.07*	*0.04*
SimCLIM (1945-2010) 5-Stn Average	4.91	3.97	3.32	2.29	1.44	0.83	0.59	0.36	0.22	0.12	0.07	0.04
2050 Rainfall Intensity (Inches/Hour)												
2050 Ensemble Median B1	5.04	4.07	3.40	2.35	1.48	0.85	0.60	0.37	0.22	0.13	0.07	0.04
2050 Ensemble Median A1B	5.09	4.11	3.44	2.37	1.49	0.86	0.61	0.37	0.22	0.13	0.07	0.04
2050 Ensemble Median A1FI	5.12	4.14	3.46	2.39	1.50	0.86	0.61	0.37	0.22	0.13	0.07	0.04
2050 Ensemble Median Average	*5.08*	*4.11*	*3.43*	*2.37*	*1.49*	*0.86*	*0.61*	*0.37*	*0.22*	*0.13*	*0.07*	*0.04*
2100 Rainfall Intensity (Inches/Hour)												
2100 Ensemble Median B1	5.12	4.14	3.46	2.39	1.50	0.86	0.61	0.37	0.22	0.13	0.07	0.04
2100 Ensemble Median A1B	5.24	4.23	3.54	2.44	1.53	0.88	0.63	0.38	0.23	0.13	0.07	0.04
2100 Ensemble Median A1FI	5.40	4.36	3.65	2.52	1.58	0.91	0.65	0.39	0.24	0.14	0.08	0.04
2100 Ensemble Median Average	*5.25*	*4.24*	*3.55*	*2.45*	*1.54*	*0.89*	*0.63*	*0.38*	*0.23*	*0.13*	*0.07*	*0.04*
Percent Change Relative to Alexandria												
2050 Ensemble	-18%	-14%	-18%	-15%	-17%	-25%	-20%	-18%	-11%	-8%		
2100 Ensemble	-15%	-12%	-16%	-13%	-15%	-23%	-17%	-15%	-8%	-5%		
Percent Change Relative to NOAA Historic												
2050 Ensemble	8%	9%	9%	9%	9%	9%	9%	9%	11%	7%	2%	0%
2100 Ensemble	11%	13%	12%	12%	12%	12%	12%	12%	15%	11%	5%	3%

10-year Return Period Discussion

Projected IDF precipitation intensity values for the 10-year return period derived from the SimCLIM for the period 2050 and 2100 are shown in Figure 4 and Table 4. The historical precipitation intensity values used for the City of Alexandria are higher than the values generated by SimCLIM for 2050 and 2100 except for the 24-hour duration. The greatest differences are shown in durations, from 5 minutes to 12 hours.

Projected precipitation intensities for the year 2050 are approximately 9 to 18 percent less than the existing Alexandria intensities for durations of 5 minutes to 6 hours and approximately 2 percent lower for 12 hours and 3 percent higher for 24 hours.

Projected precipitation intensities for the year 2100 are approximately 6 to 15 percent less than the existing Alexandria intensities for durations of 5 minutes to 6 hours and approximately 2 to 7 percent higher than Alexandria for durations of 12 to 24 hours.

While the existing Alexandria IDF curve is higher than the projected 10-year curve in 2050 and 2100 for durations below 12 hours, in contrast, the projected intensities are higher than the NOAA IDF curve used by VDOT by between 10 and 15 percent.

FIGURE 4

Projected changes in the Alexandria, VA 10-year IDF precipitation intensities for 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average compared with existing City of Alexandria, Virginia, IDF Values.
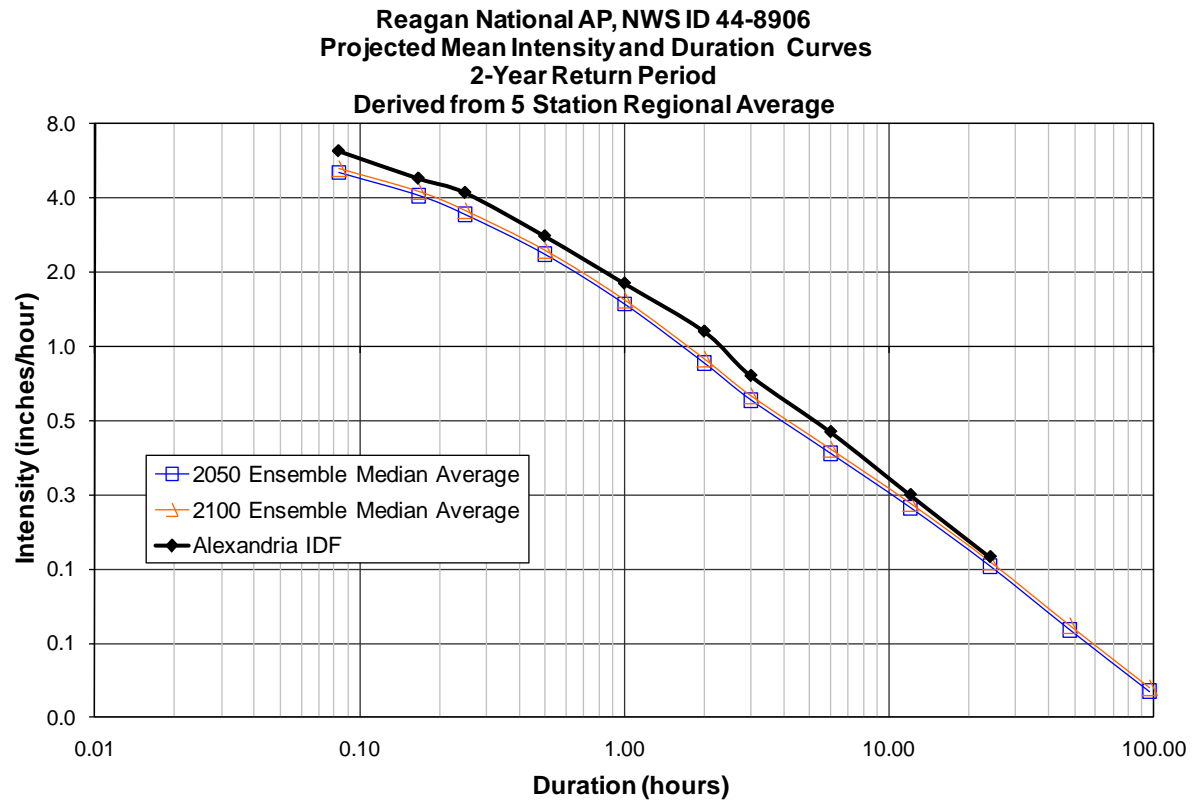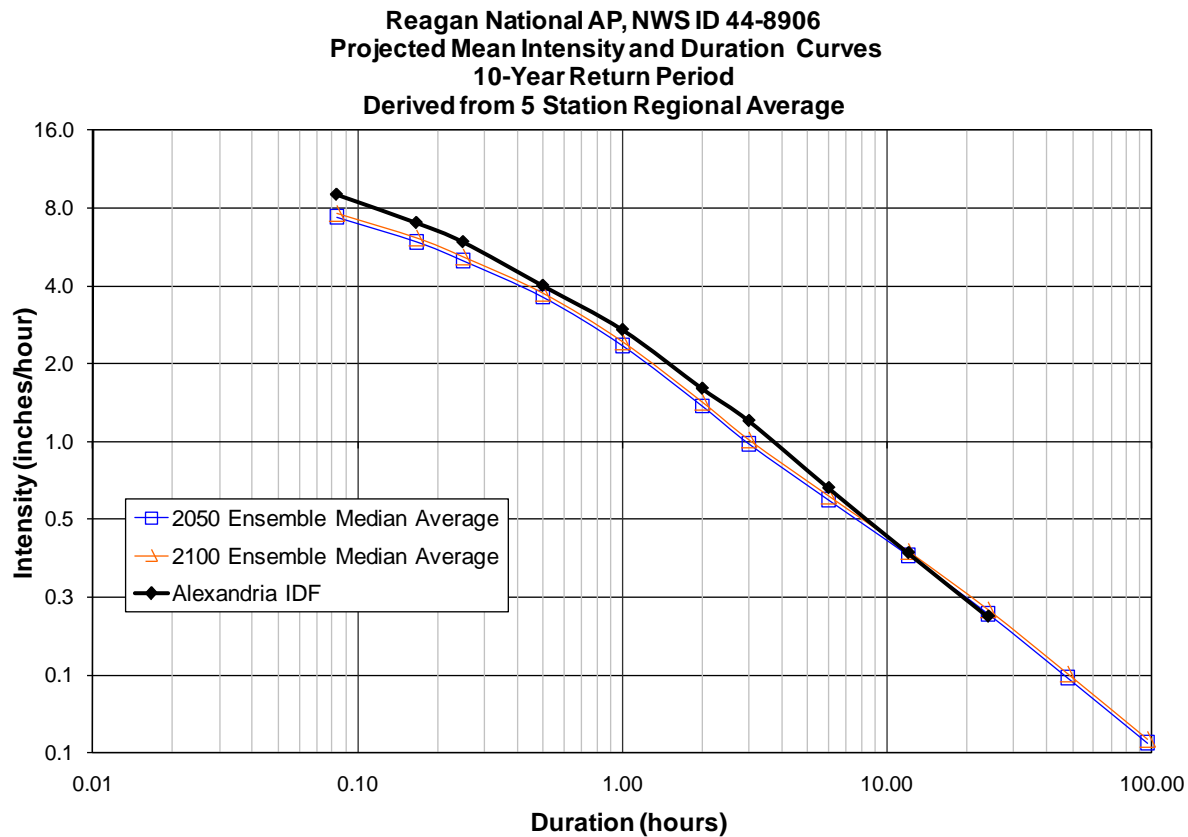
TABLE 4

Projected changes in the Alexandria, VA 10-year IDF precipitation intensities for 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average compared with existing City of Alexandria, Virginia, IDF Values. Table includes historical NOAA Atlas 14 IDF values.

10-year Return Period	Precipitation Intensity (Inches / Hour)											
	Minutes				Hours							
	5	**10**	**15**	**30**	**1**	**2**	**3**	**6**	**12**	**24**	**48**	**96**
Historic Rainfall Intensity (Inches/Hour)												
Alexandria IDF	*9*	*7*	*5.9*	*4*	*2.70*	*1.60*	*1.20*	*0.66*	*0.37*	*0.21*		
NOAA (1945-2000)	*6.73*	*5.39*	*4.54*	*3.29*	*2.14*	*1.25*	*0.89*	*0.54*	*0.33*	*0.20*	*0.11*	*0.06*
SimCLIM (1945-2010) 5-Stn Average	7.08	5.69	4.80	3.48	2.25	1.32	0.94	0.57	0.35	0.21	0.12	0.07
2050 Rainfall Intensity (Inches/Hour)												
2050 Ensemble Median B1	7.30	5.87	4.96	3.59	2.33	1.36	0.97	0.59	0.36	0.21	0.12	0.07
2050 Ensemble Median A1B	7.38	5.93	5.01	3.63	2.35	1.37	0.98	0.60	0.36	0.22	0.12	0.07
2050 Ensemble Median A1FI	7.44	5.98	5.05	3.65	2.37	1.38	0.99	0.60	0.37	0.22	0.12	0.07
2050 Ensemble Median Average	*7.38*	*5.93*	*5.00*	*3.62*	*2.35*	*1.37*	*0.98*	*0.59*	*0.36*	*0.22*	*0.12*	*0.07*
2100 Rainfall Intensity (Inches/Hour)												
2100 Ensemble Median B1	7.44	5.98	5.05	3.65	2.37	1.38	0.99	0.60	0.37	0.22	0.12	0.07
2100 Ensemble Median A1B	7.65	6.14	5.19	3.76	2.44	1.42	1.02	0.62	0.38	0.22	0.13	0.07
2100 Ensemble Median A1FI	7.92	6.37	5.38	3.89	2.52	1.47	1.05	0.64	0.39	0.23	0.13	0.07
2100 Ensemble Median Average	*7.67*	*6.16*	*5.21*	*3.77*	*2.44*	*1.43*	*1.02*	*0.62*	*0.38*	*0.22*	*0.13*	*0.07*
Percent Change Relative to Alexandria												
2050 Ensemble	-18%	-15%	-15%	-9%	-13%	-14%	-18%	-10%	-2%	3%		
2100 Ensemble	-15%	-12%	-12%	-6%	-10%	-11%	-15%	-6%	2%	7%		
Percent Change Relative to NOAA Historic												
2050 Ensemble	10%	10%	10%	10%	10%	10%	10%	10%	10%	8%	11%	14%
2100 Ensemble	14%	14%	15%	14%	14%	14%	15%	14%	14%	12%	15%	18%

NA = not applicable

100-year Return Period Discussion

Projected IDF precipitation intensity values for the 100-year return period derived from the SimCLIM for the period 2050 and 2100 are shown in Figure 5 and Table 5. The historical precipitation intensity values used for the City of Alexandria are higher than the values generated by SimCLIM for 2050 and 2100 except for the 12 and 24-hour duration. The greatest differences are shown in durations, from 5 minutes to 12 hours.

Projected precipitation intensities for the year 2050 are approximately 15 to 31 percent less than the existing Alexandria intensities for durations of 5 minutes to 3 hours, approximately 3 percent less for the 6-hour duration. Projected precipitation intensities are approximately 8 percent greater than Alexandria for the 12-hour duration and 21 percent greater for the 24 hour duration.

Projected precipitation intensities for the year 2100 are approximately 11 to 27 percent less than the existing Alexandria intensities for durations of 5 minutes to 3 hours. Projected precipitation intensities are approximately 2 percent greater than Alexandria for the 6-hour duration, 13 percent higher for the 12-hour duration, and 28 percent greater for the 24 hour duration.

While the existing Alexandria IDF curve is higher than the projected 100-year curve in 2050 and 2100 for durations below 12 hours, in contrast, the projected intensities are higher than the NOAA IDF curve used by VDOT by between 10 and 15 percent.

FIGURE 5

Projected changes in the Alexandria, VA 100-year IDF precipitation intensities for 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average compared with existing City of Alexandria, Virginia, IDF Values.

Reagan National AP, NWS ID 44-8906
Projected Mean Intensity and Duration Curves
100-Year Return Period
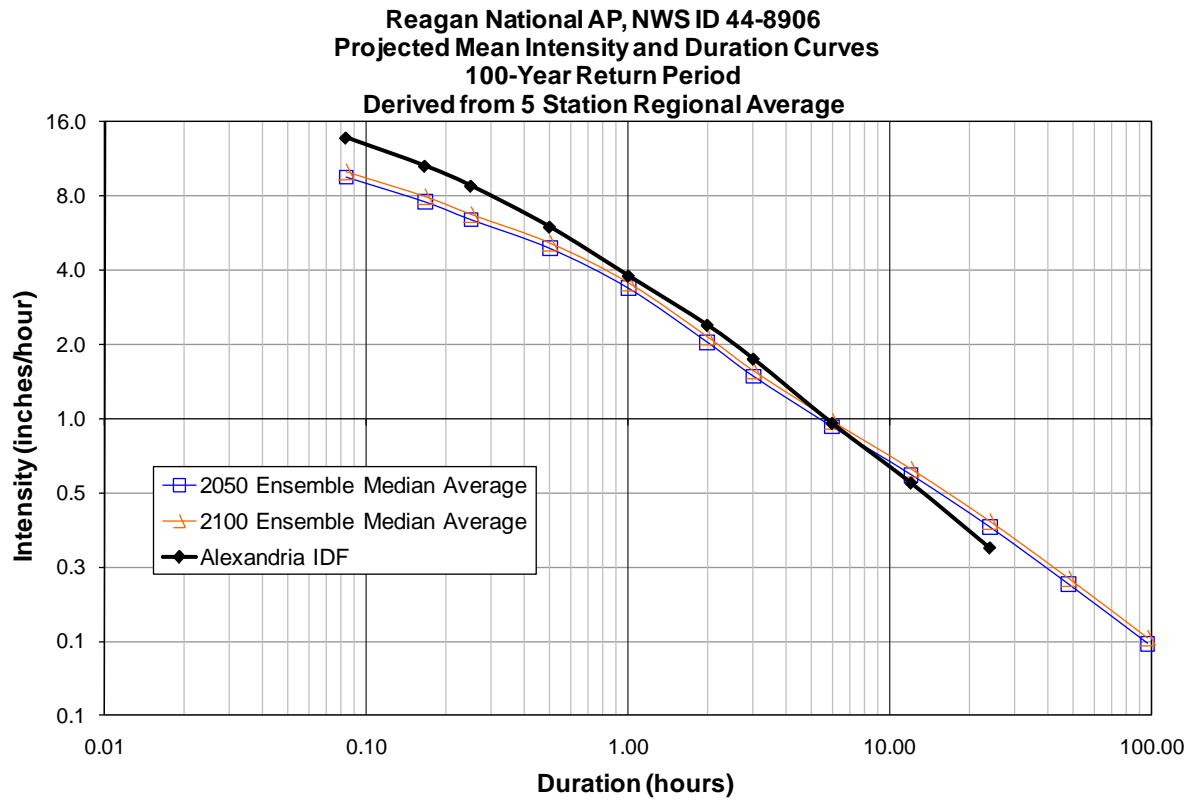Derived from 5 Station Regional Average

TABLE 5

Projected changes in the Alexandria, VA 100-year IDF precipitation intensities for 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average compared with existing City of Alexandria, Virginia, IDF Values. Table includes historical NOAA Atlas 14 IDF values.

100-year Return Period	*Precipitation Intensity (Inches / Hour)*											
	Minutes				**Hours**							
	5	**10**	**15**	**30**	**1**	**2**	**3**	**6**	**12**	**24**	**48**	**96**
Historic Rainfall Intensity (Inches/Hour)												
Alexandria IDF	*13.8*	*10.6*	*8.8*	*6*	*3.80*	*2.40*	*1.75*	*0.96*	*0.55*	*0.30*		
NOAA (1945-2000)	*9.00*	*7.16*	*6.03*	*4.62*	*3.18*	*1.92*	*1.39*	*0.87*	*0.55*	*0.34*	*0.19*	*0.11*
SimCLIM (1945-2010) 5-Stn Average	9.07	7.19	6.08	4.65	3.20	1.93	1.41	0.88	0.56	0.34	0.20	0.12
2050 Rainfall Intensity (Inches/Hour)												
2050 Ensemble Median B1	9.45	7.50	6.34	4.85	3.34	2.02	1.47	0.92	0.58	0.36	0.21	0.12
2050 Ensemble Median A1B	9.59	7.61	6.44	4.92	3.39	2.05	1.49	0.93	0.59	0.36	0.21	0.12
2050 Ensemble Median A1FI	9.69	7.68	6.50	4.97	3.42	2.07	1.50	0.94	0.60	0.37	0.22	0.12
2050 Ensemble Median Average	*9.58*	*7.60*	*6.43*	*4.92*	*3.38*	*2.04*	*1.49*	*0.93*	*0.59*	*0.36*	*0.21*	*0.12*
2100 Rainfall Intensity (Inches/Hour)												
2100 Ensemble Median B1	9.69	7.69	6.50	4.97	3.42	2.07	1.50	0.94	0.60	0.37	0.22	0.12
2100 Ensemble Median A1B	10.05	7.97	6.74	5.16	3.55	2.14	1.56	0.97	0.62	0.38	0.22	0.13
2100 Ensemble Median A1FI	10.53	8.35	7.07	5.40	3.72	2.25	1.63	1.02	0.65	0.40	0.23	0.13
2100 Ensemble Median Average	*10.09*	*8.00*	*6.77*	*5.18*	*3.56*	*2.15*	*1.57*	*0.98*	*0.62*	*0.38*	*0.22*	*0.13*
Percent Change Relative to Alexandria												
2050 Ensemble	-31%	-28%	-27%	-18%	-11%	-15%	-15%	-3%	8%	21%		
2100 Ensemble	-27%	-24%	-23%	-14%	-6%	-10%	-11%	2%	13%	28%		
Percent Change Relative to NOAA Historic												
2050 Ensemble	6%	6%	7%	6%	6%	6%	7%	7%	8%	7%	12%	11%
2100 Ensemble	12%	12%	12%	12%	12%	12%	13%	12%	13%	13%	18%	17%

City of Alexandria Projected Precipitation Estimates and Return Intervals for 2050 and 2100

A summary plot of historical Alexandria, VA 24-hour precipitation IDF values, SimCLIM estimates of historical IDF (1945 to 2100) and projected IDF precipitation amounts for the year 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average is shown in Figure 6. The Figure shows the very conservative nature of the existing Alexandria IDF values for duration from 2 to 10 years when compared to projected changes in 24-hour amounts. The existing Alexandria IDF amounts are lower for the projected 25 to 100 year return periods.

Existing City of Alexandria IDF values are shown in Table 6. Projected precipitation estimates and return intervals for Alexandria for years 2050 and 2100 are shown in Tables 7 and 8 respectively for durations from 5 minutes to 96 hours. Percent changes from the existing Alexandria IDF values for the years 2050 and 2100 are shown in Table 9.

As shown in Table 9, projected IDF values for 2050 and a 2-year return interval are less than existing Alexandria IDF values for all durations. For the 10-year return period, projected IDF values are less than existing IDF values for all durations with the exception of the 24-hour amount. For the 100-year return period, projected IDF values are less than existing IDF values for durations with the exception of the 12 and 24 hour duration which are greater than the existing IDF value.

Projected IDF values for 2100 and a 2-year return interval are less than existing Alexandria IDF values for all durations. For the 10-year return period, projected IDF values are less than existing IDF values for all durations with the exception of the 12 and 24 hour duration which is greater than the existing IDF value. For the 100-year return period, projected IDF values are less than existing IDF values for durations with the exception of the 6, 12 and 24 hour duration which are greater than the existing IDF value.

FIGURE 6

Summary plot of historical Alexandria, VA 24-hour precipitation IDF values, SimCLIM estimates of historical IDF (1945 to 2100) and projected IDF precipitation amounts for the year 2050 and 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average.
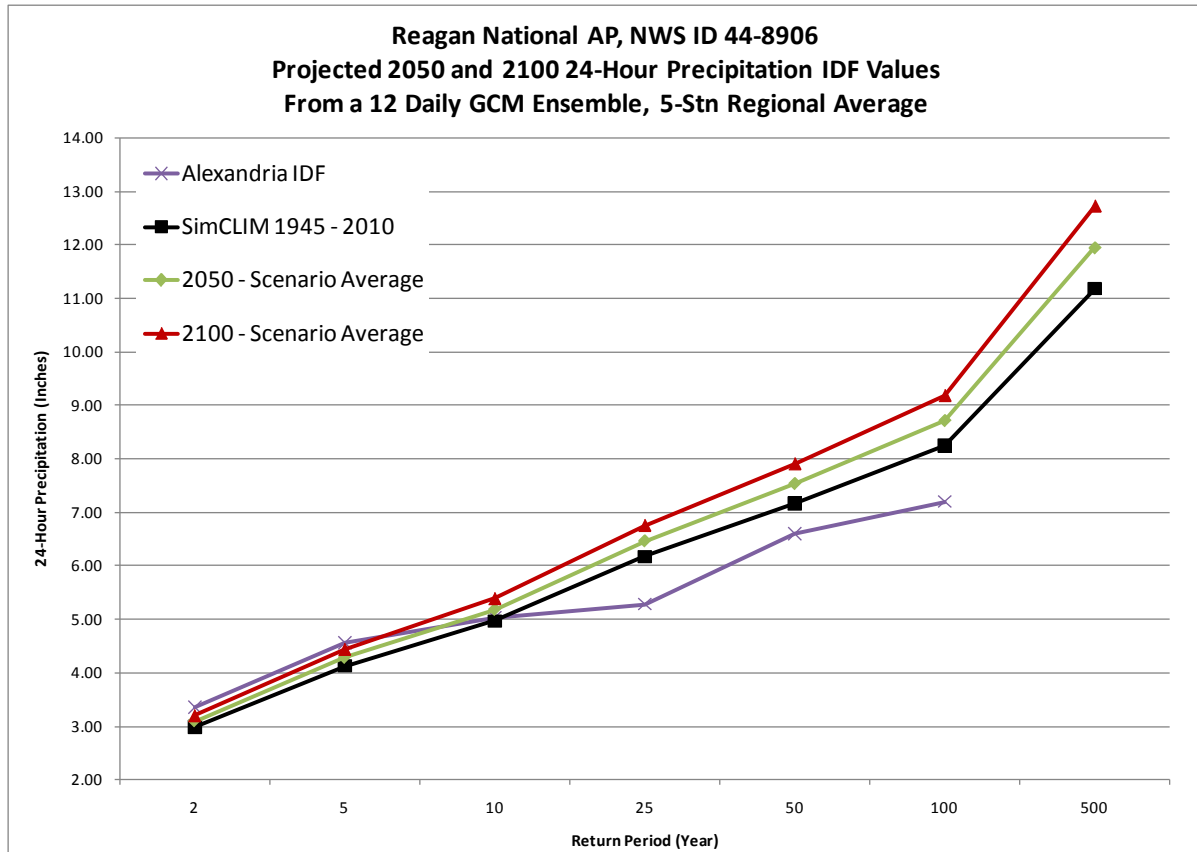

Reagan National AP, NWS ID 44-8906
Projected 2050 and 2100 24-Hour Precipitation IDF Values
From a 12 Daily GCM Ensemble, 5-Stn Regional Average

TABLE 6
Existing Alexandria IDF precipitation depth (inches), 5-minutes to 24-hours and return intervals of 2, 10 and 100 years.

Recurrence Interval (Years)	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour
2	0.52	0.80	1.05	1.40	1.80	2.30	2.28	2.70	3.00	3.36
10	0.75	1.17	1.48	2.00	2.70	3.20	3.60	3.96	4.44	5.04
100	1.15	1.77	2.20	3.00	3.80	4.80	5.25	5.76	6.60	7.20

TABLE 7
Summary table of projected Alexandria, VA IDF precipitation amounts (inches) for the year 2050 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average. Recurrence intervals from 2 to 500 years and durations from 5-minutes to 96-hours.

Year 2050	Duration											
Recurrence Interval (Years)	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour	48-hour	96-hour
2	0.42	0.68	0.86	1.18	1.49	1.72	1.82	2.22	2.67	3.10	3.42	3.83
5	0.55	0.88	1.10	1.57	2.01	2.33	2.49	3.01	3.63	4.28	4.79	5.34
10	0.61	0.99	1.25	1.81	2.35	2.74	2.94	3.57	4.36	5.18	5.85	6.55
25	0.70	1.11	1.41	2.09	2.78	3.28	3.54	4.34	5.38	6.46	7.40	8.36
50	0.75	1.20	1.51	2.27	3.08	3.69	4.00	4.94	6.21	7.54	8.73	9.95
100	0.80	1.27	1.61	2.46	3.38	4.09	4.46	5.56	7.11	8.71	10.21	11.76
500	0.89	1.42	1.79	2.84	4.08	5.06	5.58	7.17	9.51	11.95	14.40	17.08

TABLE 8

Summary table of projected Alexandria, VA IDF precipitation amounts (inches) for the year 2100 based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average. Recurrence intervals from 2 to 500 years and durations from 5-minutes to 96-hours.

Year 2100						Duration						
Recurrence Interval (Years)	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour	48-hour	96-hour
2	0.44	0.71	0.89	1.22	1.54	1.77	1.89	2.29	2.76	3.20	3.53	3.95
5	0.57	0.91	1.14	1.63	2.08	2.41	2.58	3.12	3.77	4.44	4.96	5.52
10	0.64	1.03	1.30	1.88	2.44	2.85	3.06	3.71	4.53	5.39	6.08	6.79
25	0.73	1.16	1.47	2.19	2.90	3.43	3.70	4.53	5.63	6.75	7.74	8.71
50	0.79	1.26	1.58	2.39	3.23	3.87	4.20	5.18	6.51	7.91	9.16	10.39
100	0.84	1.33	1.69	2.59	3.56	4.30	4.70	5.86	7.49	9.18	10.76	12.34
500	0.95	1.51	1.90	3.02	4.35	5.39	5.94	7.63	10.13	12.72	15.33	18.08

TABLE 9

Summary table of projected percent change from existing Alexandria, VA in IDF precipitation amounts for the year 2050 (top) and 2100 (bottom) based on an ensemble of 12 GCMs and three SRES emission scenarios from five a 5-station region average. Recurrence intervals for 2, 10 and 100 years and durations from 5-minutes to 24-hours.

Year 2050 Recurrence Interval Years	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour
2	-23%	-17%	-22%	-18%	-21%	-34%	-25%	-22%	-12%	-9%
10	-22%	-18%	-18%	-10%	-15%	-17%	-22%	-11%	-2%	3%
100	-44%	-40%	-37%	-22%	-12%	-17%	-18%	-4%	7%	17%
Year 2100 Recurrence Interval Years	5-min	10-min	15-min	30-min	60-min	120-min	3-hour	6-hour	12-hour	24-hour
2	-19%	-13%	-18%	-14%	-17%	-30%	-21%	-18%	-9%	-5%
10	-17%	-14%	-14%	-6%	-11%	-12%	-18%	-7%	2%	6%
100	-37%	-33%	-30%	-16%	-7%	-12%	-12%	2%	12%	22%

Summary

Results from 12 daily global circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in daily and annual precipitation for the years 2050 and 2100. The projected changes were applied to the historical daily precipitation record for the period 1945 to 2010 to produce updated IDF values for durations ranging from 5 minutes to 96 hours for return intervals ranging from 2 to 500 years.

The existing Alexandria, VA precipitation IDF curves can be termed conservative, meaning that for most durations less than 12 hours and return periods from 2 to 100 years, the current Alexandria IDF values are greater than the projected IDF amounts for the years 2050 and 2100. For durations greater than 12 hours, projected IDF amounts for 2050 and 2100 are greater than the existing Alexandria IDF amounts for return periods greater than 10 years.

Because of the potential infrastructure cost implications of changing drainage design criteria, the City of Alexandria is recommended to initially adopt the Atlas 14 or L-Moment results from Subtask 1.2 (which are essentially the same), which are generally lower than the City's current IDF curves, but are based on a much more complete historical data set and statistical analysis.

As part of the pilot watershed analysis of drainage facility needs in Task 2, it is recommended that the City conduct a cost-benefit analysis of the costs and risks associated with the lower Atlas 14 curves compared with the projected 2050 and 2100 IDF curves in this technical memorandum (TM) (and the sea level rise impacts on downstream hydraulic constraints). Only when costs are weighed against the risks of either reducing the IDF curves (as would be the recommendation by using Atlas 14) or increasing the IDF curves (as would be the recommendation based on projected 2100 rainfall intensities) will a better understanding of the implications of changing the City's design criteria be gained.

References

Bonnin, G.M., Martin, D., Lin, B., Parzybok, T., Yekta, M., Riley, D. 2004. "NOAA Atlas 14, Ohio River Basin & Surrounding States." U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service. Revised in 2006. Pp. 1-301.

Easterling, D.R., J.L. Evans, P.Ya. Groisman, T.R. Karl, K.E. Kunkel, and P. Ambenje. 2000. "Observed Variability and Trends in Extreme Climate Events: A Brief Review." *Bulletin of the American Meteorological Society*. 81(3). Pp. 417-425.

Groisman, P.Ya, R.W. Knight, D.R. Easterling, T.R. Karl, G.C. Hegerl, and V.N. Razuvaev. 2005. Trends in Intense Precipitation in the Climate Record. *Journal of Climate*. 18(9).Pp 1326-1350.

Groisman, P.Ya., R.W. Knight, T.R. Karl, D.R. Easterling, B. Sun, and J.H. Lawrimore. 2004. Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from in situ Observations. *Journal of Hydrometeorology*. 5(1). Pp 64-85.

Groisman, P.Ya. R.W. Knight , and T.R. Karl. 2001. Heavy Precipitation and High Streamflow in the Contiguous United States: Trends in the 20th Century. Bulletin of the American Meteorological Society, 82(2), 219-246.

Groisman, P.Ya., T.R. Karl, D.R. Easterling, R.W. Knight, P.B. Jamason, K.J. Hennessy, R. Suppiah, Ch.M. Page, J. Wibig, K. Fortuniak, V.N. Razuvaev, A. Douglas, E. Førland, and P.-M. Zhai. 1999. Changes in the probability of heavy precipitation: important indicators of climatic change. Climatic Change, 42(2), 243-283.

Hijmans, R. J., Cameron, S., Parra, J., Jones, P., Jarvis, A. 2005. "Very High Resolution Interpolated Climate Surfaces for Global Land Areas." *International Journal of Climatology*. 25: pp. 1965-1978.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001: "The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate

Change" Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.). *Cambridge University Press*. Cambridge, United Kingdom and New York, NY, USA. Pp. 1-881.

Intergovernmental Panel on Climate Change (IPCC). 2000: "Special Report on Emissions Scenarios." *Cambridge: Cambridge University Press*. http://www.grida.no/publications/other/ipcc%5Fsr/?src=/climate/ipcc/emission/.

Karl, T.R. and R.W. Knight. 1998. "Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States." *Bulletin of the American Meteorological Society*. 79(2). Pp 231-241

Kunkel, K.E., D.R. Easterling, K. Redmond and K. Hubbard. 2003: "Temporal Variations of Extreme Precipitation Events in the United States: 1895-2000." *Geophysical Research Letters*. 30(17), 1900, doi:10.1029/2003GL018052.

Kunkel, K.E., K. Andsager and D.R. Easterling. 1999. "Long-term Trends in Extreme Precipitation Events over the Conterminous United States and Canada." *Journal of Climate*. 12(8). Pp 2515-2527.

Lawrence Livermore National Laboratory. 2010. Retrieved November 2009, from Program for Climate Model Diagnosis and Intercomparison: http://www-pcmdi.llnl.gov/new_users.php

Santer, B.D., T.M.L. Wigley, M.E. Schlesinger, and J.F.B.Mitchell. 1990: "Developing Climate Scenarios from Equilibrium GCM Results." Report No. 47. *Max-Planck-Institut-für-Meteorologie*. Hamburg. Pp 1-29.

Semenov, V.A. and L. Bengtsson. 2002: "Secular Trends in Daily Precipitation Characteristics: Greenhouse Gas Simulation with a Coupled AOGCM." *Climate Dynamics*. 19(2). Pp 123-140.

U.S. Climate Change Science Program (CCSP). 2008. "Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands." *Synthesis and Assessment Product 3.3 Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration. pp. 1-180.

Warrick, R., Ye, W., Y. Li, Dooley, M., and Urich, P. 2009. " SimCLIM: A Software System for Modeling the Impacts of Climate Variability and Change." CLIMsystems Ltd. Hamilton, New Zealand.

Warrick, R. 2005. "Climate Proofing: A Risk-based Approach to Adaptation." *Asian Development Bank*." http://www.adb.org/Documents/Reports/Climate-Proofing/climate-proofing.pdf.

Wigley, T. 2008. "MAGICC/SCENGEN 5.3: USER MANUAL (version 2)." *National Center for Atmospheric Research, Boulder, CO.* pp. 1-81. http://www.cgd.ucar.edu/cas/wigley/magicc/

Acronyms and Abbreviations

CCSP	U.S. Climate Change Science Program
City	City of Alexandria, Virginia
GEV	generalized extreme value
GCM	general circulation model
IDF	intensity, duration, and frequency
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
SRES	special report on emissions scenarios
TM	technical memorandum

Appendix A
Storylines Special Report on Emissions Scenarios (SRES)

A1.   The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI); non-fossil energy sources (A1T); or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2.   The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally-oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1.   The B1 storyline and scenario family describes a convergent world with the same global population as in the A1 storyline (peaks in mid-century and declines thereafter), but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2.   The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The dataset of experiments from 12 daily models from research groups around the world is obtained from Coupled Model Intercomparison Project 3 (CMIP3) database (www-pcmdi.llnl.gov/ipcc/about_ipcc.php), representing a major advance for the evaluation of models and the generation of climate projections. The availability of a new set of systematic model experiments from the CMIP3 database represents a major advance both for the evaluation of models and the generation of climate projections. The database includes simulations of temperature and precipitation (and many other climate elements) from more than 21 monthly and 12 daily models using SRES emissions scenarios. The model output is freely available to the research community, which has resulted in unprecedented levels of evaluation and analysis. The models in the CMIP3 database represent the current state-of-the-art in climate modeling, with generally more sophisticated representations of physical and dynamical processes, and finer spatial resolution. Some models have single simulations for the 20th and 21st centuries, while others have multiple simulations (ensembles). For models with multiple simulations, ensemble-mean changes in climate have been computed. The simulations of 20th century climate were driven by observed changes in greenhouse gases and aerosols were used as baseline.

No.	Originating Group(s), Country	Model	SimCLIM Name	Horizontal Grid Spacing
1	Bjerknes Centre for Climate Research, Norway	BCCR	BCCRBCM2	~175
2	Canadian Climate Centre, Canada	CCCMA T47	CCCMA-31	~250
3	Meteo-France, France	CNRM	CNRM-CM3	~175
4	CSIRO, Australia	CSIRO-MK3.5	CSIRO-35	~175
5	Geophysical Fluid Dynamics Lab, USA	GFDL 2.0	GFDLCM20	~200
6	Geophysical Fluid Dynamics Lab, USA	GFDL 2.1	GFDLCM21	~200
7	Institute Pierre Simon Laplace, France	IPSL	IPSL-CM40	~275
8	Centre for Climate Research, Japan	MIROC-M	MIROCMED	~250
9	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, Germany/Korea	MIUB-ECHO-G	ECHO---G	~400
10	Max Planck Institute for meteorology DKRZ, Germany	MPI-ECHAM5	MPIECH-5	~175
11	Meteorological Research Institute, Japan	MRI	MRI-232A	~250
12	National Center for Atmospheric Research, USA	NCAR-CCSM	CCSM—30	~125

Appendix C
Daily GCM Extreme Value Analysis Methodology

The following method is used to analyze climate change impact on extreme precipitation events, using daily GCM outputs at their original spatial resolution (i.e. not downscaled). The steps of such a method are listed below:

1. Build a GEV distribution for one GCM baseline period (1981-2000 or 1980-1999) daily data and calculate its extreme precipitation intensity values for 7 selected return periods (2, 5, 10, 25, 50, 100, 500-year).

2. Build GEV distribution for the above GCM based on its future daily data (2050 and 2100). Select three SRES scenarios A1FI, A1B and B1 available from IPCC AR4 data archive. Calculate its extreme precipitation intensity values for the selected return periods as baseline period.

3. Calculate the difference in percentage of the extreme precipitation intensity values of between baseline and each future period.

4. Calculate the annual global average mean temperature change between the future periods and its baseline for the above GCM.

5. Normalize the extreme precipitation changes by using linear least square regression method using following equation:

$$\Delta V'_{ij} = \frac{\sum\limits_{y-1}^{m} \Delta T_y \cdot \Delta V_{yij}}{\sum\limits_{y-1}^{m} (\Delta T_y)^2}$$

$\Delta V'_{ij}$ the normalized change value a grid cell (i) and return period (j); ΔV_{yij} is the change percentage for ΔT_y for global mean temperature change for future period y; m is the number of future sample periods used.

A bi-linear interpolation method is used to obtain a finer scale extreme precipitation change pattern at the required spatial resolution. By applying the change pattern generated from daily GCM data for extreme precipitation event analysis for the study region:

6. Build GEV distribution from data of the study region and calculate the extreme precipitation values for selected return periods.

7. Extract the change pattern values from global change patterns generated in step 6.

8. Obtain the global average mean temperature change for the selected study time slices (2050, 2100) and GHG emission scenarios (A1FI, A1B and B1) in mid climate sensitivity from SimCLIM.

9. Calculate the extreme precipitation values by calculating the change patterns with global mean temperature using following equation:

$P_1 = P_o \cdot (1 + \Delta P/100 \times \Delta GMT_1)$

P_1 and P_0 represent the future and baseline extreme precipitation; ΔP is the change percentage generated from GCM data; ΔGMT, the scalar, is the change of global mean temperature increase in a future time slice.

In summary, this method can be viewed as an extension of the pattern scaling method to extreme event analysis. Work using the method for New Zealand, Australia and North America extreme rainfall analysis has generated improved results that conform to other scientific research findings.